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Natural Mechanisms of Sediment Bypassing at Tidal Inlets

by D. M. FitzGerald, N. C. Kraus, and E. B. Hands

PURPOSE: The Coastal and Hydraulics Engineering Technical Note (CHETN) described herein describes mechanisms by which sediment bypasses both natural and improved tidal inlets. The note pertains principally to inlets on alluvial or sandy shores and is a product of activities of the Coastal Inlets Research Program (CIRP), which is conducting both applied and basic studies at coastal inlets (for further information on the CIRP, see *http://cirp.wes.army.mil/cirp/cirp.html*).

BACKGROUND: Sediment transport in the vicinity of tidal inlets is complex, making it one of the most difficult systems in the coastal environment to quantify. At tidal inlets, sand moves under the combined action of waves and currents, superimposed on highly variable bathymetry with constantly changing water levels. Characterization of patterns of sand transport at inlets necessitates consideration of a wide range of temporal and spatial scales covering movement of individual sand grains (centimeters/second), migration of bed forms (meters/day), and displacement of large bars (hundreds of meters/year). This complexity extends to the process in which sand bypasses an inlet.

The dominant variables controlling the processes and rates of inlet sand bypassing have been documented from numerous case studies. The governing variables include tidal prism, inlet geometry, wave and tidal energy, sediment supply, spatial distribution of backbarrier channels, regional stratigraphy, slope of the nearshore, and engineering modifications. Engineering modifications at inlets are usually to improve navigation and typically involve a combination of jetties and maintenance of a dredged channel. Between 50 and 100 million m^3 of sand are dredged annually from Federal channels at a cost of more than \$100 million (Rosati and Kraus 2000). Potential decrease in dredging needs by exploiting natural breaching processes could offer substantial reduction in annual dredging costs. As examples, reductions in dredging frequency and/or dredged volume might be possible by aligning navigation channels with natural breaches through the ebb-tidal delta or by reconnaissance through periodic wide-area surveying to anticipate movement of large sediment bodies (Rosati and Kraus 2000). Knowledge of shoal formation and channel migrational trends at inlets can aid in the design and modification of jetties and breakwaters.

This CETN presents examples of sediment bypassing at natural and modified inlets to serve as qualitative models that can be related or adapted to other study areas. At many inlets, the dominant mode of sand bypassing can be identified from sequential aerial photographs and bathymetric maps. These types of analyses have been facilitated in recent years by improved access to Geographic Information System technology and large aerial photograph databases.

BASIC SAND-TRANSPORT PROCESSES AT INLETS: Inlet sediment bypassing is the process by which sediment moves from the updrift to the downdrift side of the inlet, involving the inlet channel and ebb-tidal delta (also referred to as the ebb-tidal shoal). Along most barrier

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **DEC 2000**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Natural Mechanisms of Sediment Bypassing at Tidal Inlets (ERDC/CHL CHETN-IV-30)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **FitzGerald, D.M.; Kraus, N.C.; and Hands, E.B.**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
This Coastal and Hydraulics Engineering Technical Note (CHETN) describes mechanisms by which sediment bypasses both natural and improved tidal inlets. It pertains principally to inlets on alluvial or sandy shores and is a product of activities of the Coastal Inlets Research Program (CIRP), which is conducting both applied and basic studies at coastal inlets.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

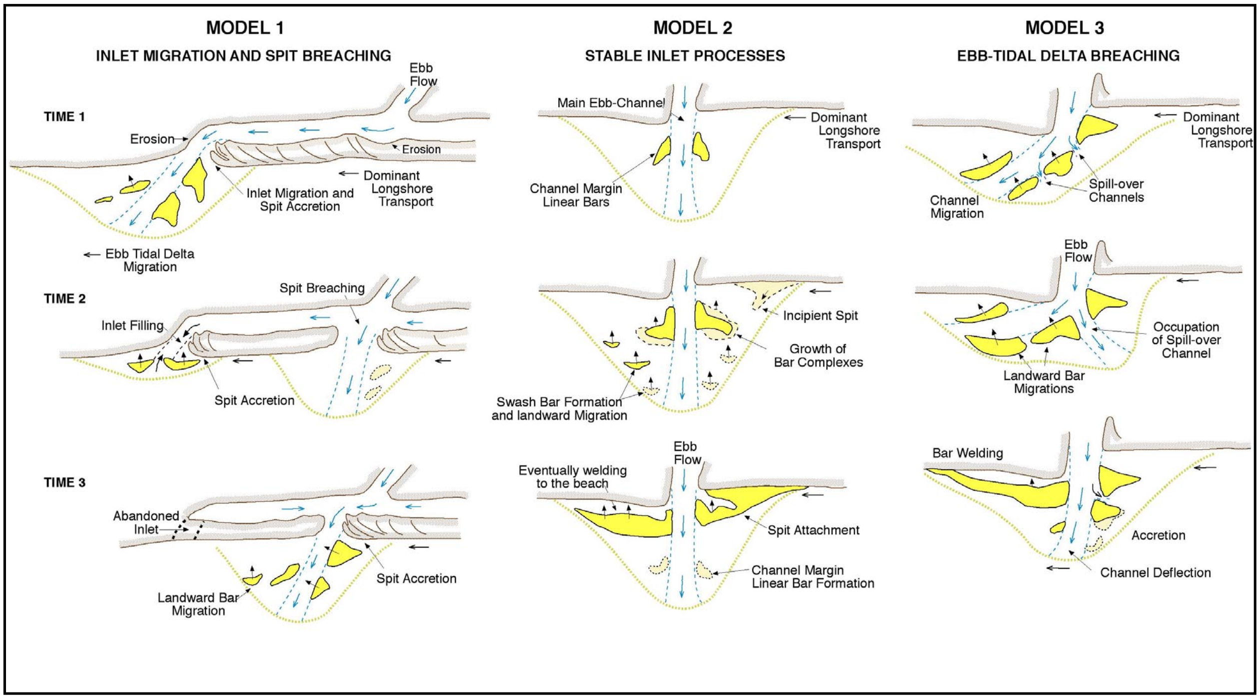
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

coasts, sand enters the main inlet channel along the beach by wave action or through marginal channels by tidal currents. Additional sand is transported into the inlet by flood-tidal and wave-generated currents over the shallow swash platform that flanks both sides of the main channel. At jettied entrances, sand may enter the inlet directly from the beach and/or shoreface in situations where the updrift jetty is short or where the beach has accreted to approach the seaward end of the jetty. In other cases, rip currents move sand toward the seaward end of jetties where flood currents can transport sediment into the inlet. The net movement of sand into the backbarrier or out the main channel or jettied channel is controlled by the dominance of the flood- versus ebb-tidal currents, respectively.

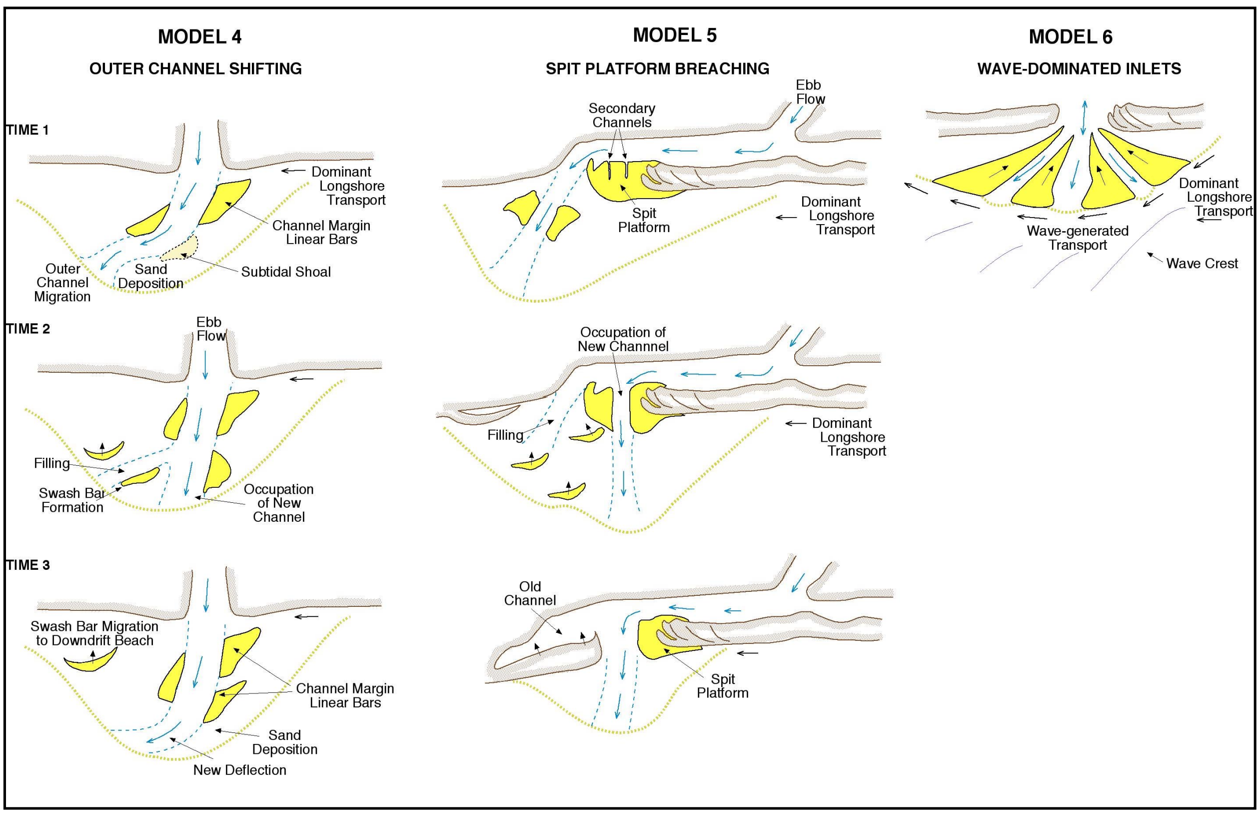
At most inlets, sand is transported into the bay during storms, when large waves increase the delivery of sand to the inlet and the storm surge produces strong flood currents. Under normal or non-storm conditions, sand in the inlet channel is moved in a net seaward direction and is ultimately deposited on the terminal lobe (outer bar). Waves shoaling and breaking on the terminal lobe generate currents, which augment flood-tidal currents and retard ebb-tidal currents. Because of the wave current interaction, sand on the terminal lobe is transported landward across the swash platform or along the periphery of the delta toward the adjacent beaches. Sediment movement onshore typically takes place in the form of large, landward migrating swash bars hundreds to thousands of meters long, 50 to 100 m wide, and 1 to 3 m in height. Along the downdrift beach, sand may be recirculated back toward the inlet or transferred farther down the barrier depending upon the morphology of the ebb-tidal delta and wave approach. These general patterns of sand transport result in sediment bypassing at inlets and are described in the following section.

MECHANISMS OF INLET SEDIMENT BYPASSING: The following examples demonstrate mechanisms by which sand is transferred to the downdrift shoreline. These conceptual models build on the pioneering work of Bruun and Gerritsen (1959) and Bruun (1966) and later research by FitzGerald (1982, 1988). Additional models are presented here based on more recent tidal inlet investigations. Both natural and structured inlets are considered.

Model 1. Stable Inlet Processes. A stable inlet is one that has a stable inlet throat (non-migrating) and a stable main ebb channel position through the ebb-tidal delta. The stability of the inlet is usually related to the channel being anchored in a substrate resistant to erosion. Bypassing at these inlets occurs through the formation, landward migration, and attachment of large bar complexes to the downdrift shoreline (Figure 1a). The development of bar complexes results from the stacking and coalescence of swash bars on the delta platform. Wave-built swash bars move onshore due to the dominance of landward flow created by wave swash. Their stacking results from a decrease in the rate of onshore migration. As the bars migrate up the shoreface, they gain a greater and greater intertidal exposure. Consequently, wave swash, which causes their onshore movement, operates over an increasingly shorter period of the tidal cycle. This developmental process at Price Inlet, SC (Figure 2) was responsible for delivering 100,000 m^3 of sand to the downdrift beach. The time frame for these bars to form and migrate onshore is highly variable but usually takes from 4 to 10 years. The size of bars and the volume of sand moved onshore generally increases with increasing inlet size. Bars migrating onshore from ebb-tidal deltas of Friesian Inlets along the German North Sea coast commonly break up and lose

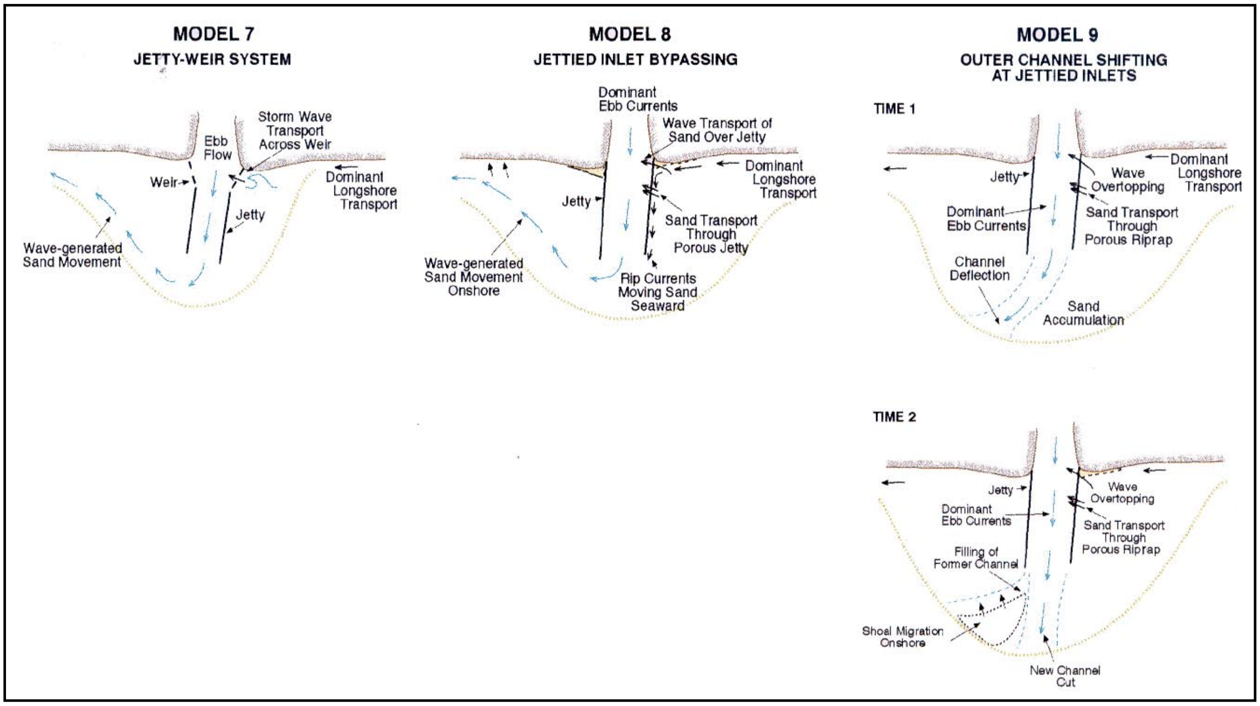


a. Models 1-3



b. Models 4-6

Figure 1. Conceptual models (Continued)



c. Models 7-9

Figure 1. (Concluded)

Model 2. Ebb-Tidal Delta Breaching. Ebb-tidal delta breaching occurs at tidal inlets that have stable throat positions, but whose main ebb channels cyclically migrate downdrift (Figure 1a). The dominant direction of longshore transport at these sites produces a preferential accumulation of sediment on the updrift side of the ebb-tidal delta. The sediment accumulation causes a downdrift deflection of the main ebb channel, which at some inlets may ultimately impinge against the downdrift inlet shoreline. This pattern of channel migration commonly induces erosion along the adjacent beach. A severe deflection of the main channel produces flow at the inlet that is hydraulically inefficient. Eventually, this condition results in the ebb discharge being diverted to a more direct seaward pathway through the ebb-tidal delta.

The breaching process can occur gradually over a period of 6 to 12 months or catastrophically during a single storm when discharge of floodwaters increases the scouring of the ebb currents. Once formation of the new channel is completed, it will convey most of the inlet tidal prism. Thus, the abandoned channel gradually fills with sediment deposited by both tidal and wave-generated currents. The breaching process commonly results in the bypassing of a large portion of the ebb delta sand. Some of this sand fills the old channel, while the rest forms a subtidal or intertidal bar complex that migrates onshore ultimately attaching to the landward beach. These bars are identical to the ones previously described for the stable inlet processes and contain equal or greater volumes of sand. The entire developmental process takes from 5 to 10 years to complete.

Model 3. Inlet Migration Spit Breaching. Sand transported along the beach and deposited in a tidal inlet constricts the inlet throat decreasing the flow area. As Escoffier's (1940) stability

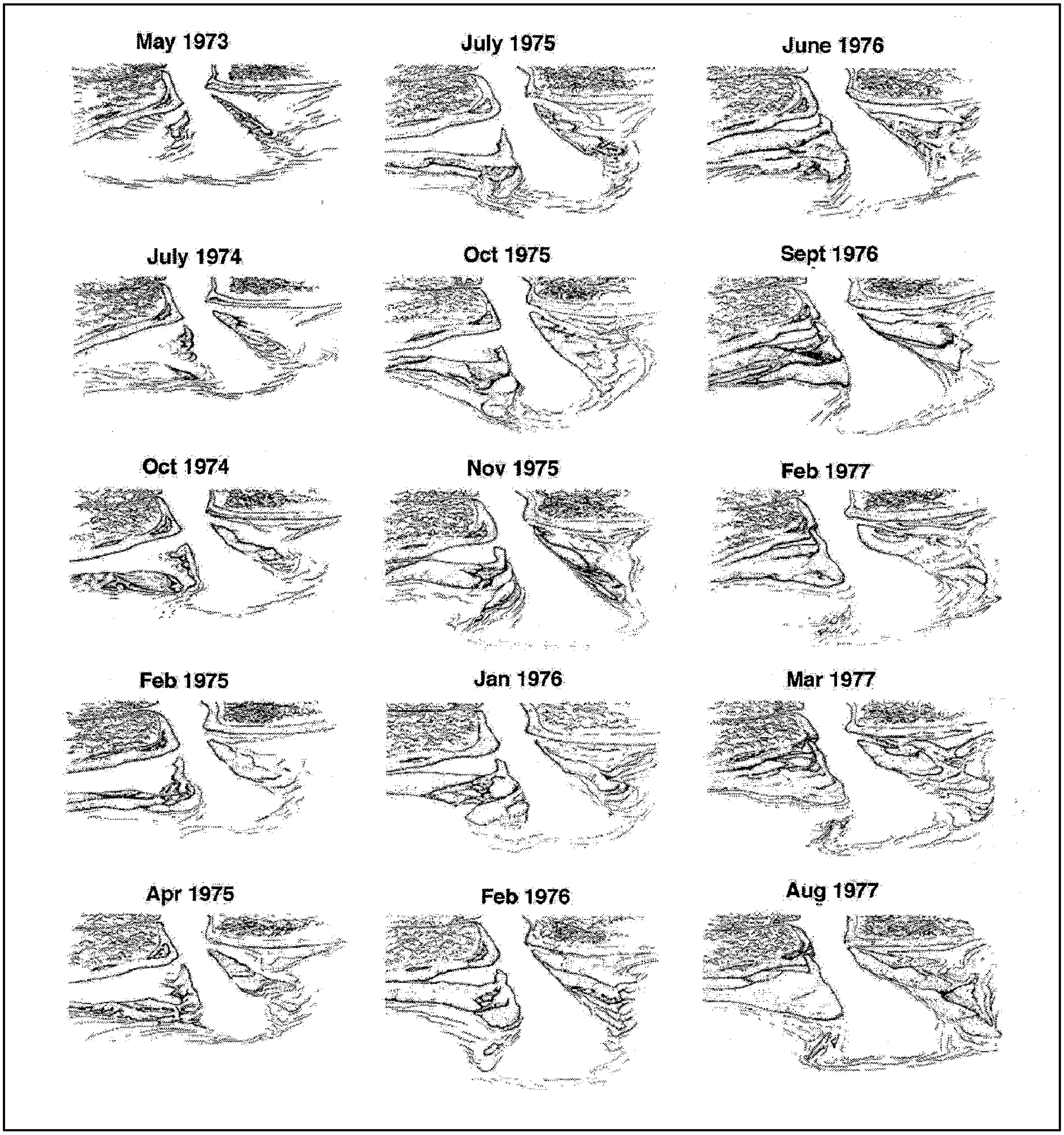


Figure 2. Changes in ebb-tidal delta morphology at Price Inlet, SC (May 1973 to August 1977)

concept states, the constriction causes an increase in current velocity which leads to greater scouring of the inlet channel and re-establishment of the equilibrium channel cross-sectional area. Because longshore transport along most coasts adds sand predominantly to one side of the inlet, the opposite side erodes preferentially causing the inlet to migrate (Johnson 1919). The rate of migration is dependent on sediment supply, wave energy, tidal current strength, and composition of the channel banks. If a migrating inlet becomes entrenched into resistant sediments, further migration will be impeded. Shallow inlets tend to migrate and deeper inlets tend to be more stable because there is a greater likelihood that their channels have scoured into

semi-indurated sediments. As an inlet migrates, it leaves behind a series of curved beach ridges that define the updrift spit. Inlet migration commonly lengthens the inlet channel, which connects the open ocean to the backbarrier bay, lagoon, or marsh and tidal creek system. Elongation of the inlet channel increases frictional resistance of tidal flow thereby reducing tidal range in the bay.

Differences in tidal phase and tidal range between the ocean and backbarrier can augment the breaching of the spit and formation of a new (relocated) tidal inlet (Figure 1a). Spits are usually breached during storms when waves erode the beach and dune system, reducing the width of the barrier. Storm surges produce washovers (precursors of inlets) and increase tidal flow. The new inlet is commonly located along the updrift spit at a position where the barrier is narrow and the backbarrier tidal prism is easily accessed. The hydraulically favorable position of the new inlet promotes capture of the old inlet's tidal prism and its eventual closure. The end product of the spit breaching process is that a large quantity of sand is transferred from the updrift to the downdrift inlet shoreline.

Model 4. Outer Channel Shifting. This mechanism of inlet sediment bypassing is similar to ebb-tidal delta breaching, but is limited to the seaward end of the main ebb channel and involves smaller volumes of sand (Figure 1b). In this process, the inner portion of the main channel remains in a fixed position while the outer channel is deflected downdrift because of preferential accumulation of sand on the seaward, updrift side of the swash platform. As the outer portion of the channel becomes more deflected, which at some inlets can produce a right-angle bend, flow through the outer portion of the channel becomes increasingly less efficient. Eventually, a new channel is cut through the distal portion of the ebb delta that shortens the pathway of flow. Cutting of a new channel is commonly initiated during high spring tides when peak flows occur in the channel. The sand that had been located on the updrift side of the outer channel and is now on the downdrift side has bypassed the inlet.

As the bypassed sand moves onshore by flood-tidal and wave-generated currents, it is commonly molded into a large swash bar that migrates landward and attaches to the downdrift beach. These bars are usually much smaller than those produced through ebb-tidal breaching processes but may still contain 5,000 to 50,000 m^3 of sand. At some inlets, the bypassing of sand by outer channel shifting may occur between the longer episodes of major ebb-tidal delta breaching. At other inlets, particularly those having deep channels, outer channel shifting may be the dominant mode of sediment bypassing. At these sites the inner channel may be entrenched in resistant sediments precluding channel migration. Willapa Bay Inlet in southwest Washington is an example of this type of channel system, although the bypassed sand does not form a bar complex that migrates onshore to the downdrift shoreline (Hands and Shepsis 1999).

Model 5. Spit Platform Breaching. At most migrating inlets, the updrift barrier spit is fronted by a large intertidal spit platform. The platform may extend from 100 to more than 1,000 m into the inlet producing a highly asymmetric channel configuration. In Model 5, large quantities of sand are bypassed when a new channel is breached through the spit platform (Figure 1b). The major channel in the backbarrier usually runs parallel to the rear of the spit as it nears the inlet and then turns to flow around the spit platform. This pattern is analogous to flow through a river meander bend consisting of a point bar (spit platform) and channel cut bank

(downdrift side of inlet throat). Spit platforms usually exhibit considerable relief having many small shallow channels and numerous bars and bed forms. Spit accretion and downdrift extension of the spit platform increase the length of the inlet channel, thereby decreasing flow efficiency between the ocean and bay. Inlets of this type are susceptible to inlet channel shortening particularly during storms when surges elevate water levels. At these times, early ebb discharge from the backbarrier flows out the main channel as well as in a short cut route across the spit platform.

At some inlets, seaward flow across the spit platform may become channelized in one of the secondary shallow channels. Deepening of this channel may avulsively form a new, shorter channel for water to exit the inlet. At other inlets the spit platform breaching process occurs gradually over a period of 1 to 2 years. Depending upon the size of the inlet, this can result in very large volumes of sand bypassing the inlet. Not only is a portion of the spit platform transferred to the downdrift side of the inlet as the old channel fills, but also most of the former ebb-tidal delta sediment is transported onshore to the downdrift beach as flow is diverted to the new updrift inlet channel. This process of inlet sediment bypassing tends to be repeated every 4 to 8 years due to the continual enlargement and downdrift extension of spit platform, which result from ongoing spit accretion and inlet migration and the oblique approach of the major backbarrier creek at the inlet.

Model 6. Wave-Dominated Inlets. Wave-dominated inlets are defined as those in which the distribution of sand bodies and general morphology of the ebb-tidal delta indicate the dominance of wave-generated rather than tide-induced sediment transport. These inlets are usually small (widths < 200 m) with shallow main ebb channels (depths < 6 m). They have sand shoals that are pushed close to the mouth of the inlet, producing a slightly arcuate ebb delta shape. The overall shallow nature of the distal portion of the ebb delta, much of which may be exposed at low tide, coupled with its gently arcuate shape, allows waves to transport sand along the periphery of the delta, especially at high tide (Figure 1b). The transport of sand along the outer delta takes place in the same manner as that in the surf and breaker zones. Sediment bypassing at these inlets occurs continuously, unlike the episodic landward bar migration dominant in the other models. This mechanism of bypassing is similar to Bruun and Gerritsen's (1959) "bar-bypassing model" and has been mathematically modeled by Kraus (2000).

Model 7. Jetty-Weir Inlet Bypassing. This mode of inlet sediment bypassing occurs at certain jettied inlets containing one or two weirs with no settling basin (Figure 1c). Weirs are the landward, submerged portions of jetties that allow sediment that is moving in the longshore transport system to enter the jettied channel. This process is most active during storms when energetic waves suspend large amounts of sand and strong longshore currents reach velocities of a meter per second or more. During these conditions sand is easily transported over the weir and into the adjacent channel. In the design inlet, sand entering the inlet via the weirs is transported seaward by the dominant ebb-tidal currents. Ideally, sediment is eventually transported beyond the end of the jetties where tidal and wave-generated currents move the sand onshore to the downdrift beach. At some inlets, such as the entrance to Charleston Harbor, SC, a second weir extending from the downdrift shoreline is present to reduce the amount of sand trapped by downdrift jetties. This type of bypassing system works well only when the ebb currents clearly dominate the flood currents and when the ebb discharge is capable of transporting the littoral

sands out the jettied channel. In addition, tidal and/or wave-generated currents must be sufficiently strong to rework the sand onshore that is deposited at the mouth of the jettied channel.

Model 8. Jettied Inlet Bypassing. The amount of sand that bypasses jettied inlets depends on a number of factors such as jetty length, inlet size, channel depth, tidal current strength, and ebb-tidal delta morphology. There are few jetties that bypass sand at a rate equal to the net longshore transport rate. In most cases, the excess sand accumulates along the updrift beach, causing progradation or is deposited in the jettied channel and has to be dredged. Sand that bypasses the inlet is either moved offshore by rip currents or enters the jettied channel through wave overtopping and/or movement through porous riprap (Figure 1c). Storm waves and large wave swell produce strong longshore currents, which are directed toward the jetty along the updrift shoreline. This obstruction commonly produces intense rip currents that transport littoral sands offshore to the ebb-tidal delta. At some inlets, such as Merrimack River Inlet, MA, storm waves occasionally transport sand over the updrift jetty and into the adjacent channel (Hubbard 1975).

At sites where jetty construction consists of porous riprap, sand can move through gaps between the stones during periods of high wave energy and/or high water. Sand deposited in the jettied channel by various mechanisms is transported seaward by dominant ebb currents to the ebb-tidal delta. The presence of jetties serves to funnel the ebb discharge thereby displacing the ebb delta offshore into deeper water. The deeper overall depth of the ebb delta reduces the effect of waves and retards the formation of bar complexes. Sediment bypassing is accomplished through transport along the outer bar by wave action primarily during storms.

Model 9. Outer Channel Shifting at Jettied Inlets. At some jettied inlets, such as Moriches Inlet on Long Island, NY, the ebb-tidal delta is dynamic, and channel migration is an active process. Sand bypassing at inlets of this type occurs in a manner similar to Model 4 where the outer channel is deflected downdrift due to the preferential buildup of sand on the updrift side of the main ebb channel (Figure 1c). During periods of high tidal discharge a new pathway is cut through the deflecting sand shoal producing a straighter channel that is hydraulically more efficient. The breaching produces a packet of sand that has been transferred from the updrift to the downdrift side of the delta. Some of this sand is then transported onshore by wave action, completing the bypassing process.

FINAL OBSERVATIONS: Sediment bypassing at tidal inlets occurs through a range of processes that have been identified in six models of natural inlets and three models of jettied inlets. A commonality of unstructured inlets is that sand bypassing ultimately results in the formation, landward migration, and attachment of large bars to the downdrift shoreline. The amount of sediment contained in these bars varies between 50,000 to more than 200,000 m^3 of sand. The actual volume is dependent on inlet size inlet, ebb-tidal delta morphology, rate at which sand is delivered to the inlet, and the type of bypassing mechanism. Bar welding at these inlets is a repetitive process with a frequency of 4 to 10 years. FitzGerald (1988) and Gaudiano and Kana (2000) have documented episodic welding of bar complexes onto the downdrift beach at inlets in South Carolina. An exception to this trend are the wave-dominated inlets where

bypassing occurs continuously whereby sand is moved primarily by wave action along the terminus of the delta to the downdrift beach.

It is emphasized that even at inlets where sand bypassing occurs in the form of large bars, additional sand is moved to the downdrift shoreline in a continuous mode. The relative magnitude of this process as compared to bar migration varies from inlet to inlet and is a research problem that has received little attention. Likewise, the processes of sediment bypassing at jettied inlets are less well studied and are being investigated in the CIRP.

ADDITIONAL INFORMATION: This note was produced under the Coastal Inlets Research Program (CIRP) by Dr. Duncan M. FitzGerald, Department of Earth Sciences, Boston University, and by Dr. Nicholas C. Kraus and Mr. Edward B. Hands, both at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this note can be addressed to Dr. FitzGerald at *Dunc@bu.edu*; to Dr. Kraus at *Nicholas.C.Kraus@erdc.usace.army.mil*; or to Mr. Hands at *Edward.B.Hands@erdc.usace.army.mil*. For further information about the CIRP, please contact the CIRP Technical Leader, Dr. Kraus at the e-mail address furnished or by telephone at (601) 634-2016. This CETN should be cited as follows:

> FitzGerald, D. M., Kraus, N. C., and Hands, E. B. (2001). "Natural mechanisms of sediment bypassing at tidal inlets," ERDC/CHL CHETN-IV-30, U.S. Army Engineer Research and Development Center, Vicksburg, MS. (*http://chl.wes.army.mil/library/publications/chetn*)

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